Decision Models for Habitat Restoration

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Overview

- Decision Models
- Pacific Salmon Context
- Watershed Mgt / Competing Objectives / MIP
- Passage Removal / Spatial Relations / NLIP
- Erosion Control / Project Timing / MDP
- Erosion Control / Monitoring / POMDP

Decision Models

- Ingredients
  - decision variables
  - objective function
  - constraints
- Examples
  - classical optimization
  - Markov decision (‘adaptive mgt’)
  - Bayesian
  - fuzzy control, robust optimization, etc.

Decision Models: Why Bother?

- Identify desirable actions

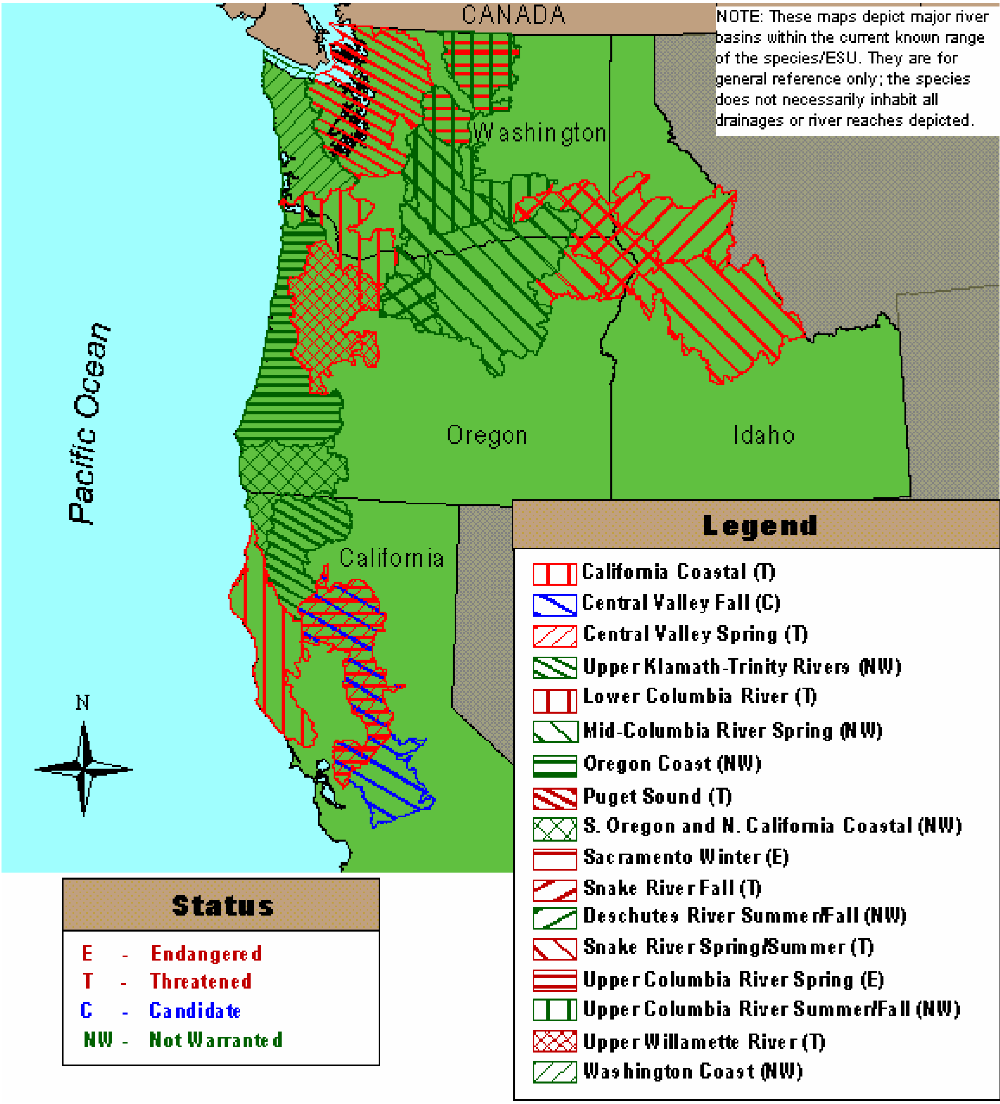
- Assess trade-offs

- Identify research needs

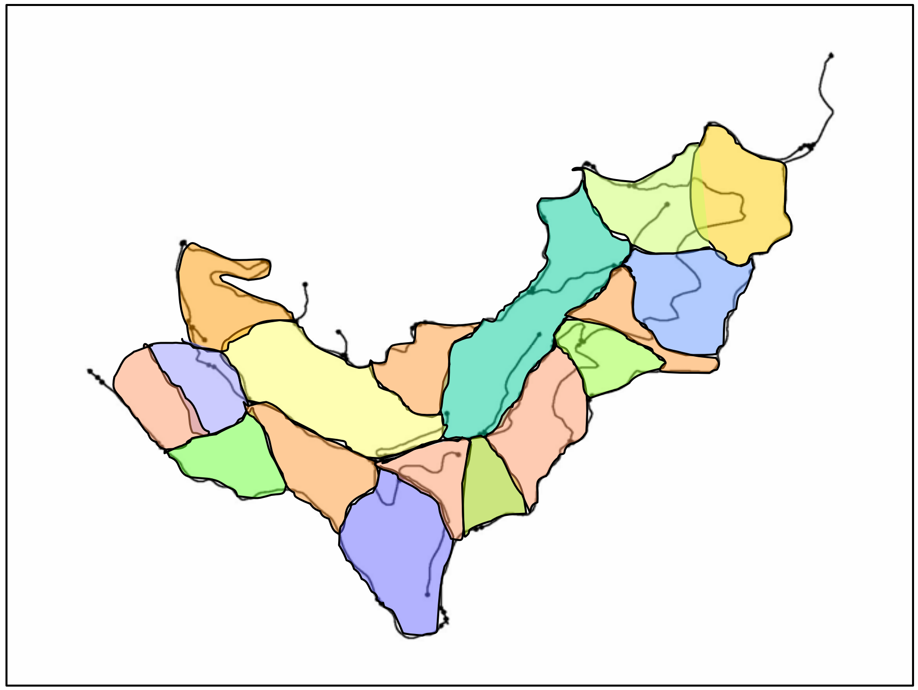
- Focus discussion among stakeholders

Salmonid Habitat Restoration

- ESA Listings (27 ESUs)
- > $110 mn on habitat restoration (2001) in CA
- Threats to freshwater salmon habitat
  - Sediment
  - Passage barriers
  - Temperature
  - Water diversion, mining, etc.



Question 1: What are the tradeoffs between erosion control and timber production in a watershed? What's the best mix?

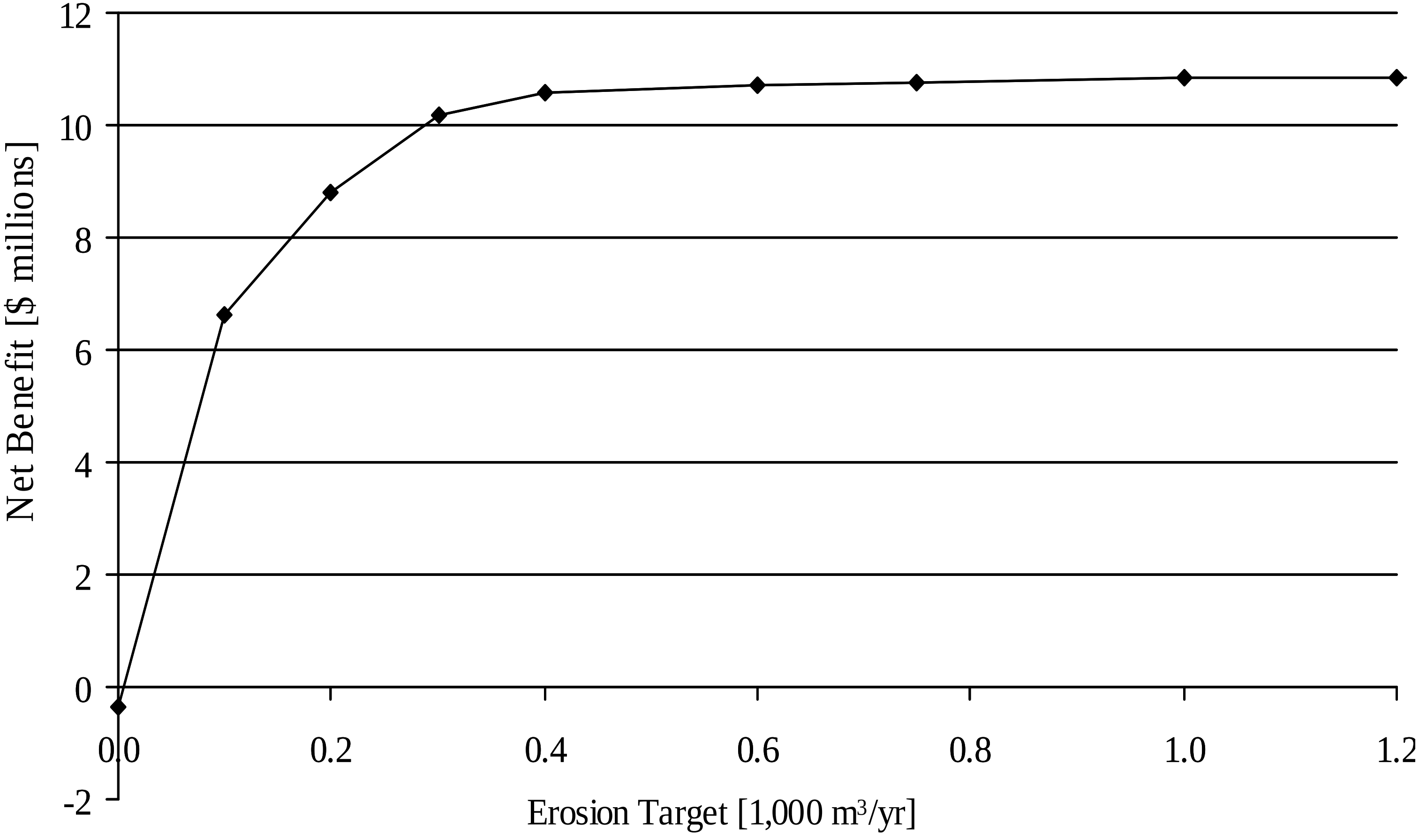


Model 1: MIP (Spatial + Deterministic + Myopically Dynamic)

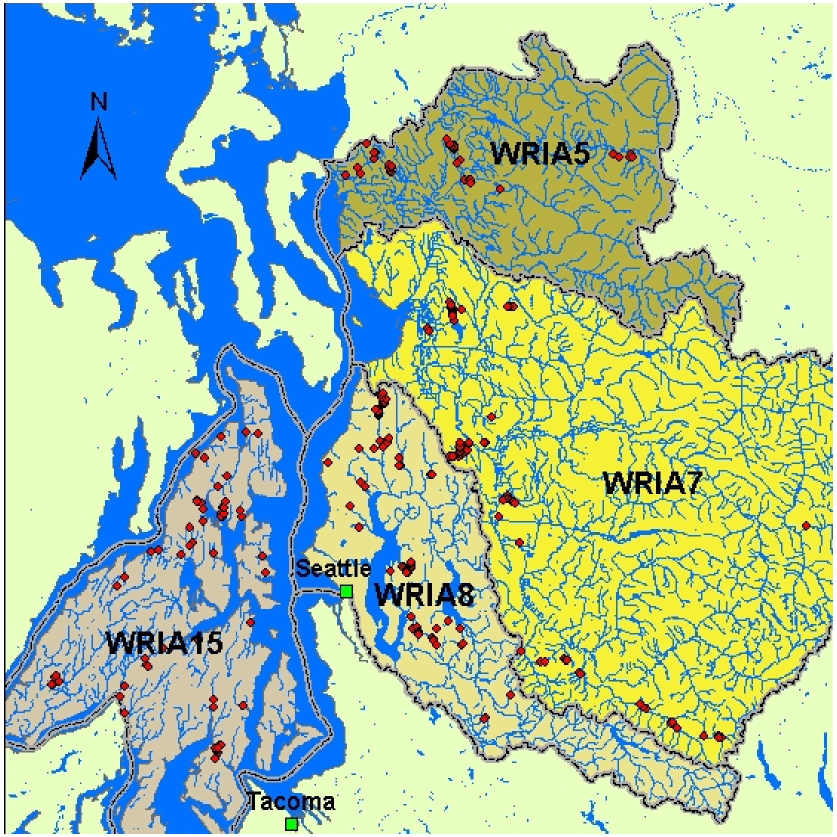
Model 1: A Mixed-Integer Program

- Goal: Max net benefit
- Benefits: Timber and access
- Costs: Logging, transport, and erosion control
- Constraints:
  - Max erosion
  - Access and traffic flow
  - Inter-temporal

Model 1: Results



Question 2: Which fish passage barriers should be removed with a given budget?



Model 2: NLIP (Spatial + Deterministic)

Model 2: NLIP

Goal: maximize the increase in upstream accessibility, subject to a budget constraint.

max $z = \sum_j v_j \left[\prod_k (p_k^o + \sum_i p_{ik} x_{ik}) - \prod_k p_k^o \right]$ (sum of increases in passability-weighted stream length)

subject to

$\sum_i x_{ij} \leq 1$	$\forall j$	(only one project can be chosen)
$\sum_j \sum_i c_{ij} x_{ij} \leq b$		(only \$b can be spent in total)
$x_{ij} \in \{0,1\}$	$\forall i$	(projects are all-or-nothing)

where

i = project index

j = barrier index

k = barrier index for barriers downstream of j (and including j)

v = habitat above barrier j until next upstream barrier

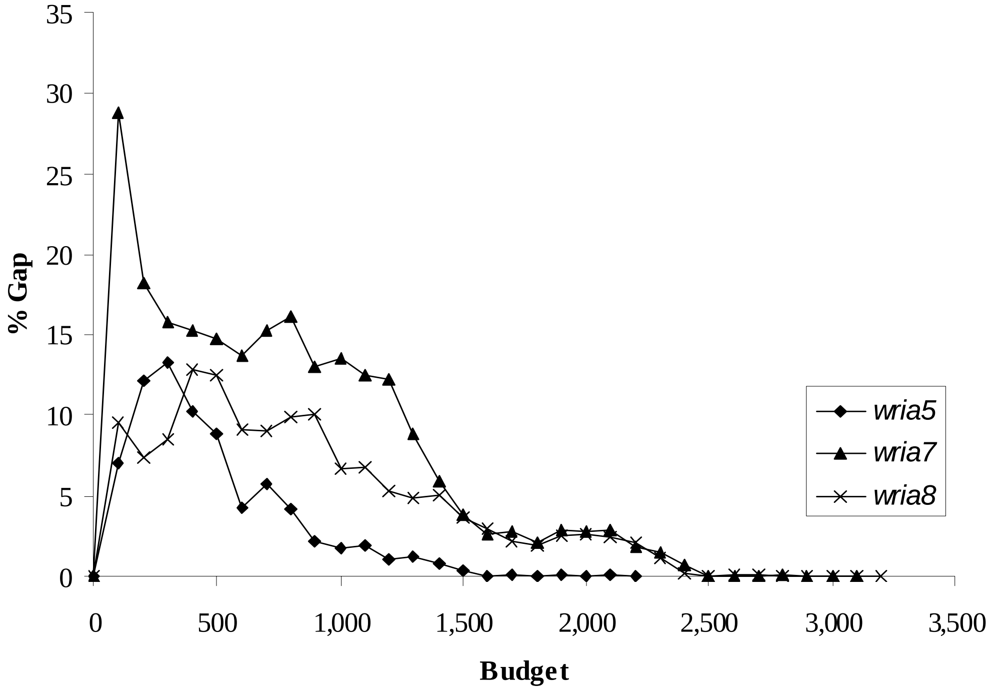
p = percent passability index for each barrier

x = project variable (do or don't)

c = project cost

b = total budget

Model 2: Results



Percent deviation from optimum of a sorting and ranking procedure for three watersheds in western Washington, as a function of budget.

Question 3: What's the best way to control logging road erosion under uncertainty?

Model 3: Markov Decision Process (Stochastic + Dynamic)

→ 'Adaptive Mgt'

Model 3: Problem Characteristics

- Possible treatments:
  - Maintain *status quo* road *(cheap, high-risk)*
  - Upgrade road *(moderate expense and risk)*
  - Remove road *(expensive, low-risk)*
- State variables:
  - Landslide volume
  - Surface erosion volume
  - Crossing-failure volume

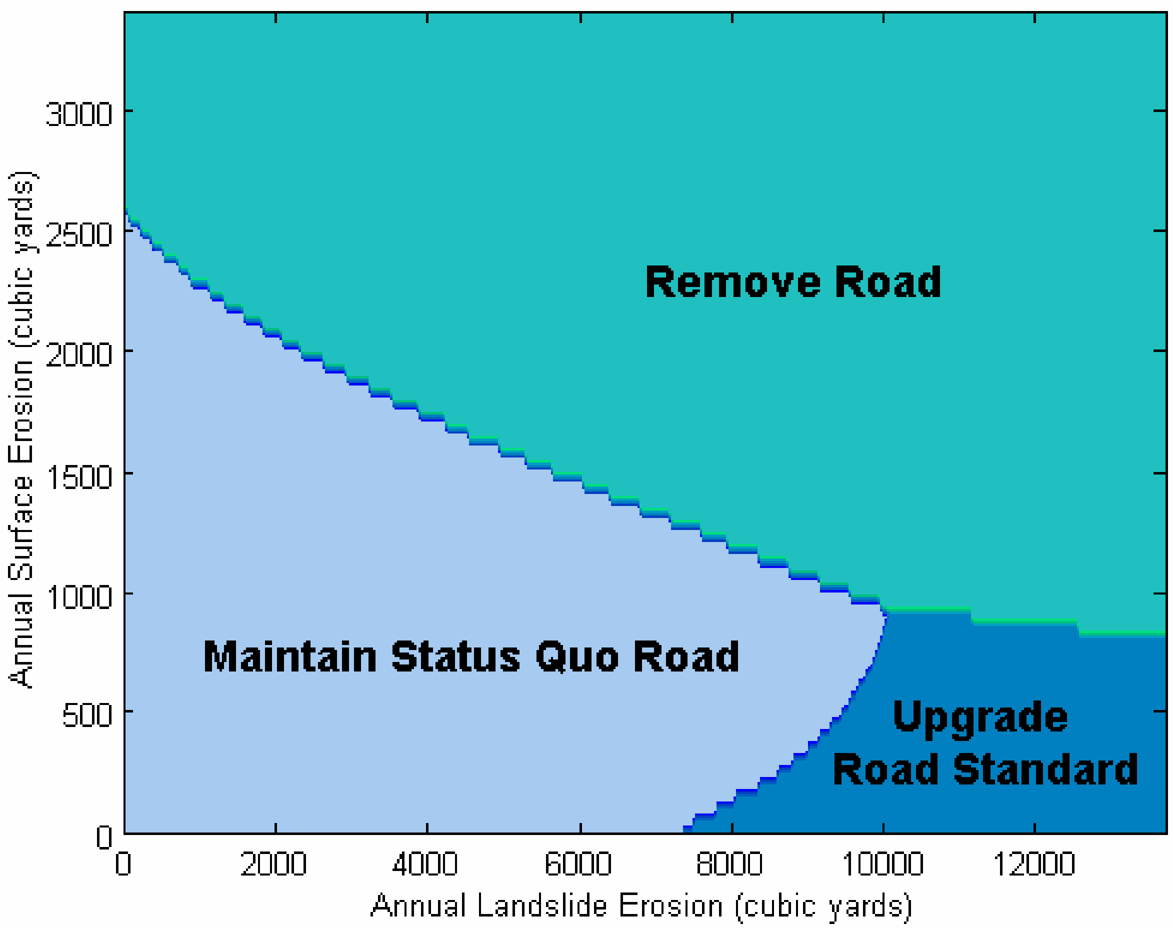
Model 3: SDP Representation

$$main\ \ problem: \quad V_1(x_t) = \min_u \{ \quad C_1(x_t) + \frac{1}{1+\rho} E[V_1(C_1(x_{t+1})) \mid x_t, s_t = 1], \quad U + \frac{1}{1+\rho} E[V_2^*(x_{t+1}) \mid x_t, s_t = 1], \quad R_1 \}$$

$$sub-problem: \ V_2(x_t) = \min_u \{ \ \ C_2(x_t) + \frac{1}{1+\rho} E[V_2(C_2(x_{t+1})) \mid x_t, s_t = 2], \qquad R_2 \}$$

where	$V(x)$	=	the expected present and future cost of optimal treatment
	x	=	vector of erosion volumes
	u	=	control
	$C_1(x)$	=	annual road maintenance costs for *status quo* road
	$C_2(x)$	=	annual road maintenance costs for upgraded road
	ρ	=	manager's discount rate
	s	=	2 if the road has already been upgraded 1 if the road is still *status quo*
	U	=	lump-sum cost of road upgrade
	R_1	=	lump-sum cost of *status quo* road removal
	R_2	=	lump-sum cost of upgraded road removal

Model 3: Results



Question 4: When is it worth the trouble to learn how much erosion we have?

North Fork Caspar Cr., plugged culvert Rd 5

(Question 4b: In general, what is the best mix of learning and doing?)

Model 4: POMDP (Stochastic + Dynamic + Noisy)

POMDP Generalities

- MDP = {S, P, A, W}
  POMDP = {S, P, Θ, R, A, W}
- MDP maps state → action
  POMDP maps beliefs → action
- Unknown state variables,
  known parameters*

POMDP & Other Approaches

- dual control
  - ‘active adaptive mgt’
  - POMDP is dual control, sort of
  - control engineers vs AI types
  - estimation of time-varying parameters
- dynamic Bayes decision
- stochastic programming
- robust programming

POMDP Value Function

$$V_t(\pi) = \max_a \left[\sum_i \pi_i q_i^a + \sum_{i,j,\theta} \pi_i p_{ij}^a r_{j\theta}^a V_{t+1}[T(\pi \mid a, \theta)] \right]$$

where

π_i = probability of being in state i

q_i^a = immediate reward for taking action a in state i

p_{ij}^a = probability of moving from state i to state j after taking action a

$r_{j\theta}^a$ = probability of observing θ after taking action a and moving to state j

T = function updating beliefs based on prior and θ

POMDP Example

- When is erosion monitoring worth the trouble?
- States = {Good Road, Bad Road}
- Decisions = {Do Nothing, Monitor, Treat}
- Observations = {Good Road, Bad Road}

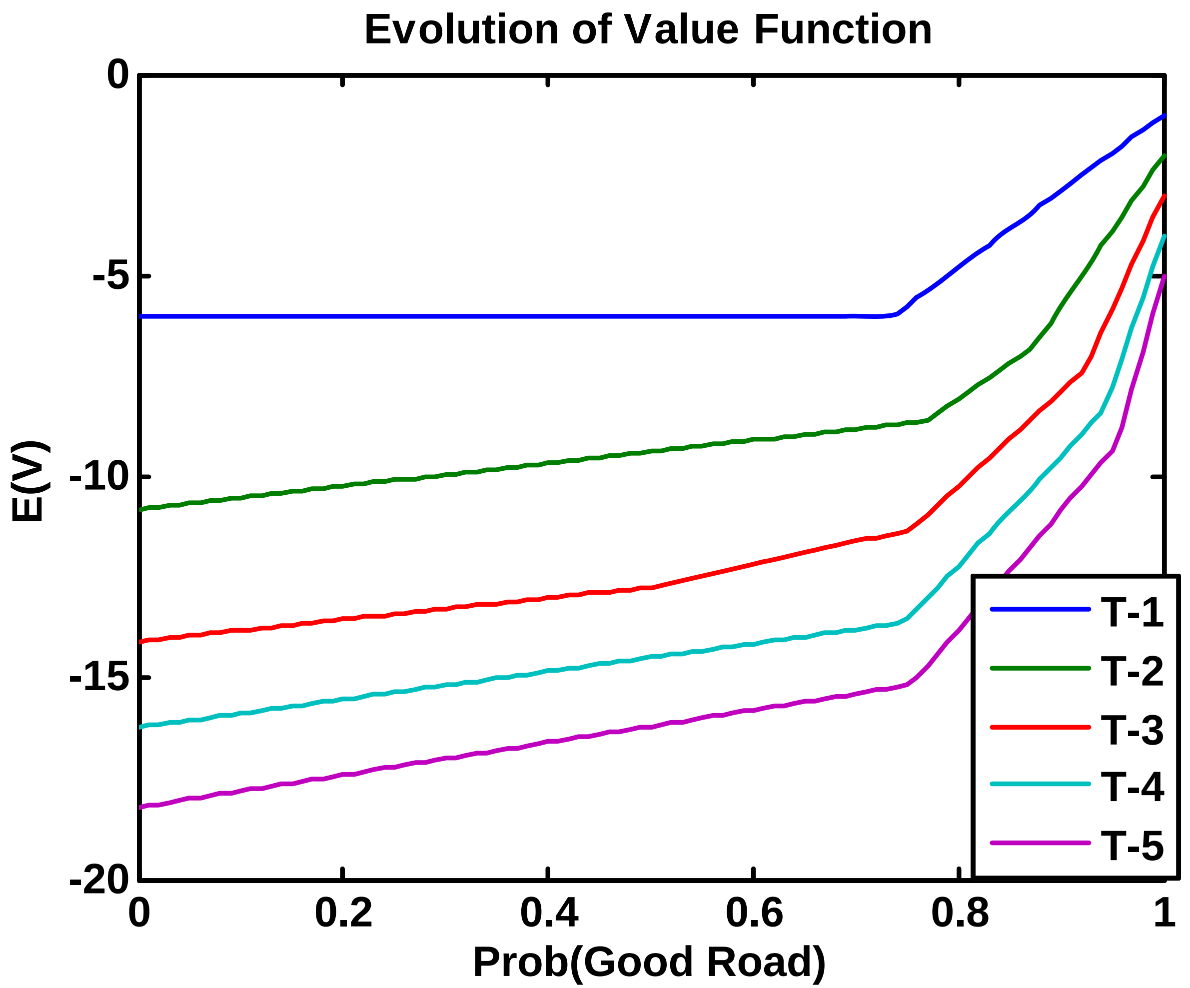
POMDP Example (cont)

$$P_{ij}^{1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad P_{ij}^{2} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad P_{ij}^{3} = \begin{bmatrix} 0.95 & 0.05 \\ 0.80 & 0.20 \end{bmatrix}$$

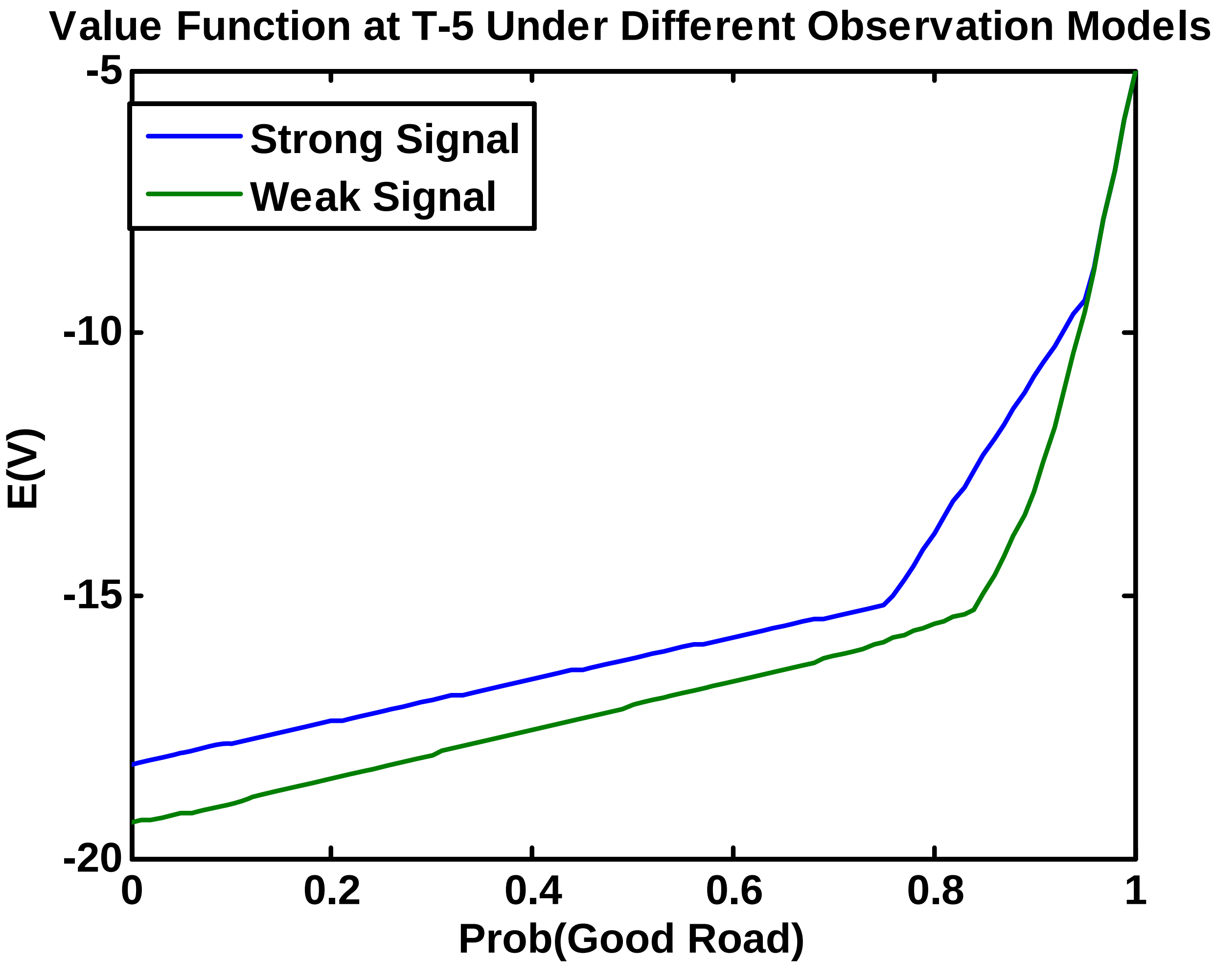
$$R_{j\theta}^{1} = \begin{bmatrix} 0.6 & 0.4 \\ 0.4 & 0.6 \end{bmatrix} \quad R_{j\theta}^{2} = \begin{bmatrix} 0.9 & 0.1 \\ 0.1 & 0.9 \end{bmatrix} \quad R_{j\theta}^{3} = \begin{bmatrix} 0.5 & 0.5 \\ 0.5 & 0.5 \end{bmatrix}$$

$$W_{ij\theta}^{1} = \begin{bmatrix} -1 & -20 \\ -1 & -20 \end{bmatrix} \quad W_{ij\theta}^{2} = \begin{bmatrix} -3 & -15 \\ -3 & -15 \end{bmatrix} \quad W_{ij\theta}^{3} = \begin{bmatrix} -6 & -6 \\ -6 & -6 \end{bmatrix}$$

Results for a 5-period problem



Results (cont)



POMDP Assessment

- POMDP is good
  - noisy data is everywhere
  - monitoring funds are scarce
  - applicable to planning and behavioral models
- Drawbacks
  - computation
  - assumes (stochastic) dynamics are known

Decision Models Assessment

- Two big technical issues
  - parameter uncertainty
  - spatial and temporal together
- To do: Bayesian DP, neuro-DP, robust portfolio optimization, data envelopment analysis, fuzzy control, decision analysis, sequential hypothesis testing
- Models not easily generalizable, need careful development and application with each new problem
- Potential bang-for-buck gains are substantial

The Egg Model of Ecosystem Management